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Construction and Test of an Inductor Alternator

Electrical Engineering

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CONSTRUCTION AND TEST OF AN INDUCTOR ALTERNATOR

BY

JOHN HENRY DURFEE
DON JOHN CHARLES DREW

THESIS

For the Degree of Bachelor of Science
in Electrical Engineering

COLLEGE OF ENGINEERING
UNIVERSITY OF ILLINOIS

PRESENTED, JUNE, 1906

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June 1, 1906

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

DON JOHN CHARLES DREW and JOHN HENRY DURFEE

ENTITLED CONSTRUCTION AND TEST OF AN INDUCTOR ALTERNATOR

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF Bachelor of Science in Electrical Engineering

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HEAD OF DEPARTMENT OF Electrical Engineering

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Introduction

Owing to the extensive use of the inductor alternator, the Electrical Engineering Department has for some time desired to obtain a machine of this type for use in the laboratory. Such a machine was first sought in the market, but it was found that no machine of suitable size could be obtained. This made it necessary to design and build a machine especially for the laboratory.

With this end in view, the designing of the required machine was assigned to Mr. D.H. Kelly as a Thesis problem.

The object of the present Thesis is to construct this alternator according, as far as possible, to the design submitted

by the mills, and to thoroughly test the completed machine.

The writer's motive in taking such a thesis was that it presented special opportunities for learning methods of shop practice and construction work, and also offered some practical testing experience which could be gotten in no other way outside a commercial testing room.

General Description.

The machine designed was a 7½ K. W. alternator of the inductor type, having two separate armature windings which could be connected either in parallel to produce 110 volts, or in series to produce 220 volts. The speed of the motor was intended to be variable so as to produce a range of frequency from 60 cycles up to 180 cycles per second.

Construction of the Inductor alternator.

Pattern Making.

Using the blue prints made by Mr. Kelly, the pattern making was begun in June, 1905. The large pattern for the armature ring was first built. It was constructed of one and two inch material sawed out in quarter circles on the band saw and fitted together. The successive layers were glued and nailed together, the nails being placed so as not to interfere with turning. Two rings were built up in this way each having a thickness equal to one-half the width of the armature ring. After the glue had set the rings were fastened one at a time to the end turning plate of the large lathe and turned on the outside to the proper shape and size for the two halves of the pattern. In order to get the

proper curvature for the ring, a templet was made from ¼ wood, and the ring was then turned to fit the templet.

In order to avoid the necessity of making a separate core-box, the inside of the annular ring pattern was turned out so that the core could be made inside the pattern itself. This method also facilitated the setting of the cores in the moulds as they were again placed inside the pattern when the mould was rammed up in the flask. After the ring was turned up the feet and small core prints shown in Plate I were mortised in, and carved into proper shape.

All the patterns shown in this plate, except the pedestal were made by the writer during the summer of 1905.

Castings.

After the patterns were completed the required number of moulds were made in the University Foundry. Good castings were obtained from all

This except the armature ring, the mould for which became cracked due to shrinkage in taking off the cope. Another mould was made for this - and a very good casting was obtained.

Machine Work.

The machine work was done in the University Machine Shop, principally by the writer, although some assistance was rendered by the members of the sophomore class.

Plate II shows the armature ring in the boring mill which is set to bore out the inside of the casting to receive the laminated steel pole pieces.

Pole Pieces.

The sheet steel of which the pole pieces were built up was 15 mills thick. The coating of iron oxide made in the process of rolling and annealing was the only insulating material used between the sheets. The sheets were first cut into rectangular pieces which were of the proper width for the poles but

were made about ¼" longer than necessary, to allow for machining on both ends. The pole pieces were then assembled and held in place between the retaining plates by two rivets and a bolt through each pole. <Plate III shows the rotor and armature. The part marked (3) is the pole piece of the rotor, and (5) is the armature pole piece.

Winding.

Field Coil.

The large field coil shown in (1) Plate III was wound with number 16 wire on a brass spool from which it was insulated by two thicknesses of oiled linen. As the layers were wound on every fourth one was painted with S.P.B. insulating paint. When the winding was finished, the coil was taped with two layers of cotton tape and given several coats of insulating paint. Leads of heavy rubber-insulated wire were soldered on, and the coil was tested for insulation resistance. It was found

to be perfect with 500 volts impressed between the coil and the brass spool.

Armature Coils

Coils for the armature, twenty in number, were wound on a cast iron former made for the purpose, the core of which was just the size of the armature pole pieces. Number 7 double cotton covered copper wire was used, and some difficulty was encountered in bending it around the sharp angles of the former.

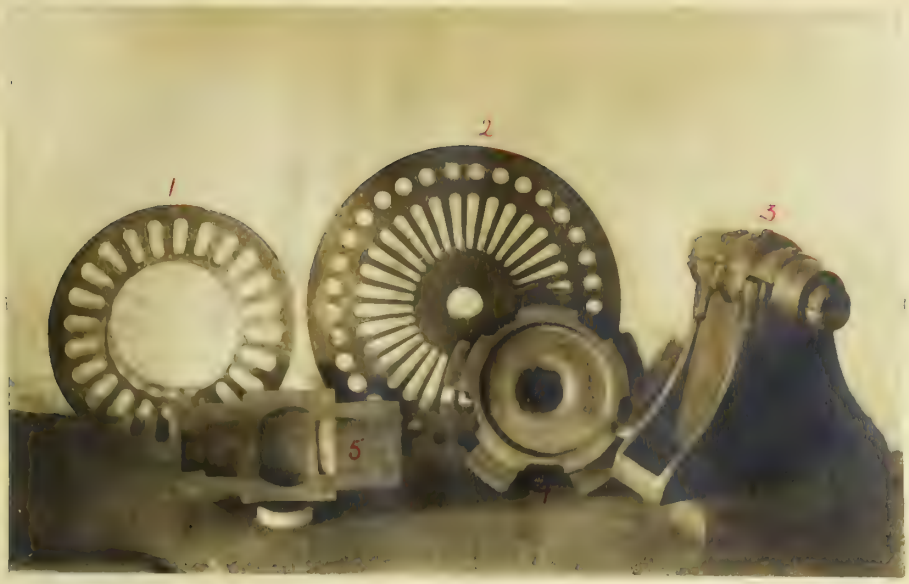
After being formed the coils were covered with two thicknesses of tape and put in position on the armature as shown in Plate III.

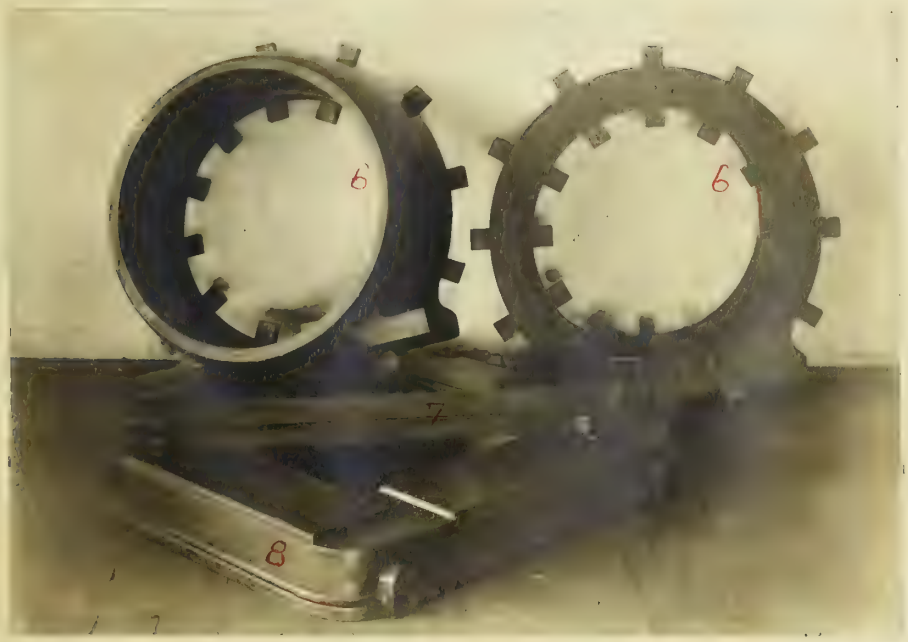
Centering and Balancing the Rotor.

Centering the rotor was a problem requiring considerable time and patience. The air gap was only 3/32" wide and in order to get an even distribution of the flux, it must be exactly equal on all sides. To facilitate the adjustment the pedestals were made about 1/16" short. The rotor and pedestals were placed in position and

the air gaps on each side of the rotor were adjusted so that they were nearly equal. Wedges were put in to hold the parts in this position while the holes were bored to hold the pedestals to the base. The bolts were then put in loosely and the air gap at the top and bottom of the rotor was adjusted by shimming up the pedestal with sheet steel and paper. By this means the air gap on all sides was adjusted to within 0.002 of an inch of being equal.

When the machine was first started, it had considerable vibration. This was found to be due to the rotor being not exactly balanced. The rotor was balanced on knife edges by drilling out some of the metal on the heavy side until it did not turn when placed in any position. It was then put back in the machine and was found to run very smoothly.

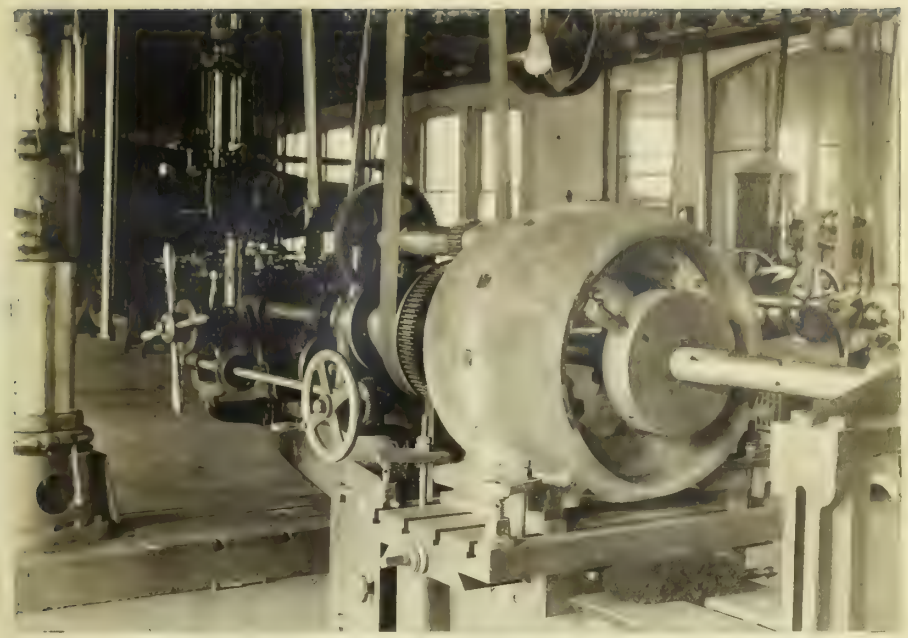




PATTERNS:

1. Field Spool
2. End Plate
3. Pedestal
4. Poles
5. Core Box.
6. Armature Yoke.
7. Slide Rail.
8. Base.

PLATE I.



ARMATURE YOKE IN BORING MILL

PLATE 11.

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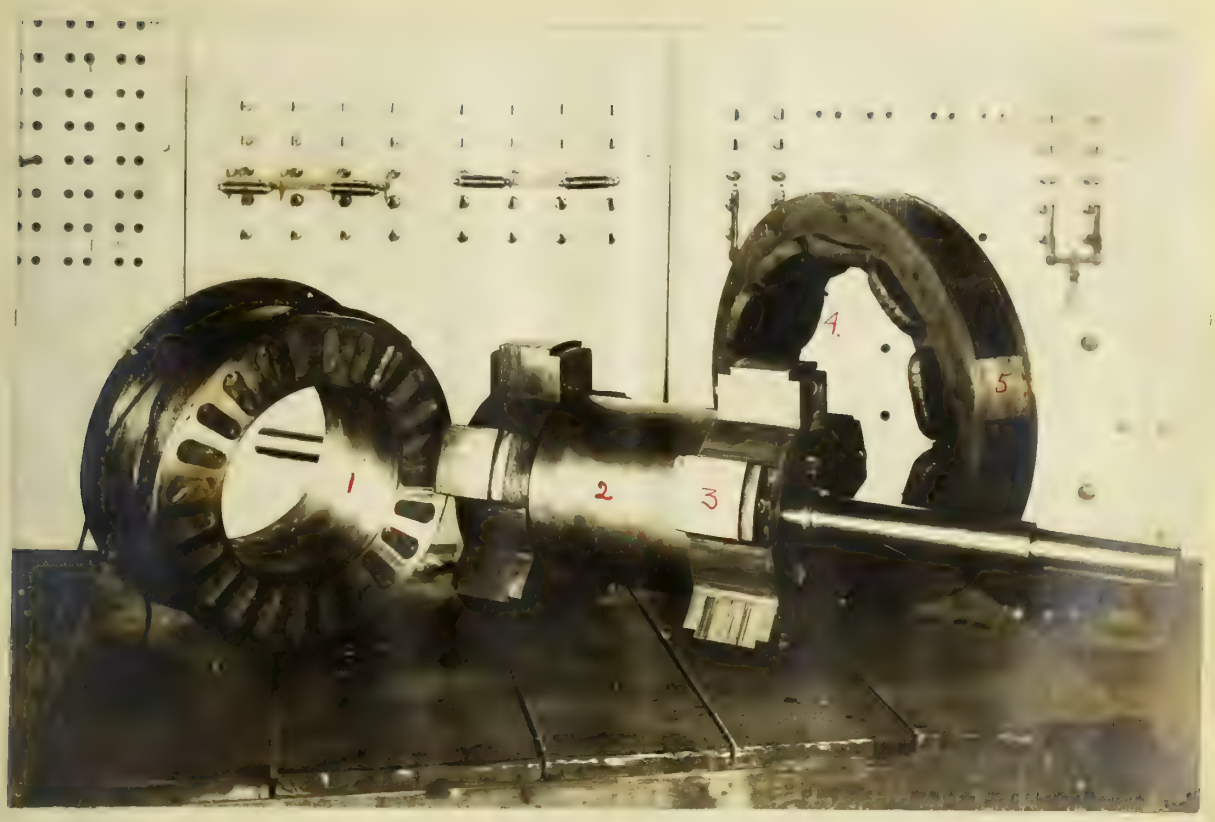

1. Field Coil. 4. Armature.

2. Rotor. 5. Laminations.

3. Poles.

PLATE III.

INDUCTOR ALTERNATOR

PLATE IV.

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Tests of the Inductor Alternator.

Magnetization Curves.

Tests were made with the machine at operating temperature.

The machine was run at constant frequency while the field current was varied from zero up to a value which produced a voltage somewhat above normal, and again reduced to zero. Readings were taken of field current and pressure. Curves were plotted using terminal volts as ordinates and field current as abscissas. The curves are shown in Plate V. Curve No. I is the curve given at 120 cycles, and No. II is that given at 60 cycles. The difference in the value of the ordinates of the ascending and descending curves show that the hysteresis will be quite heavy in the machine.

The fact that there is no prominent knee to the curves may be accounted for

by the fact that the magnetic circuit is made up of materials of different magnetic permeabilities each of which comes to the saturation point at a different time.

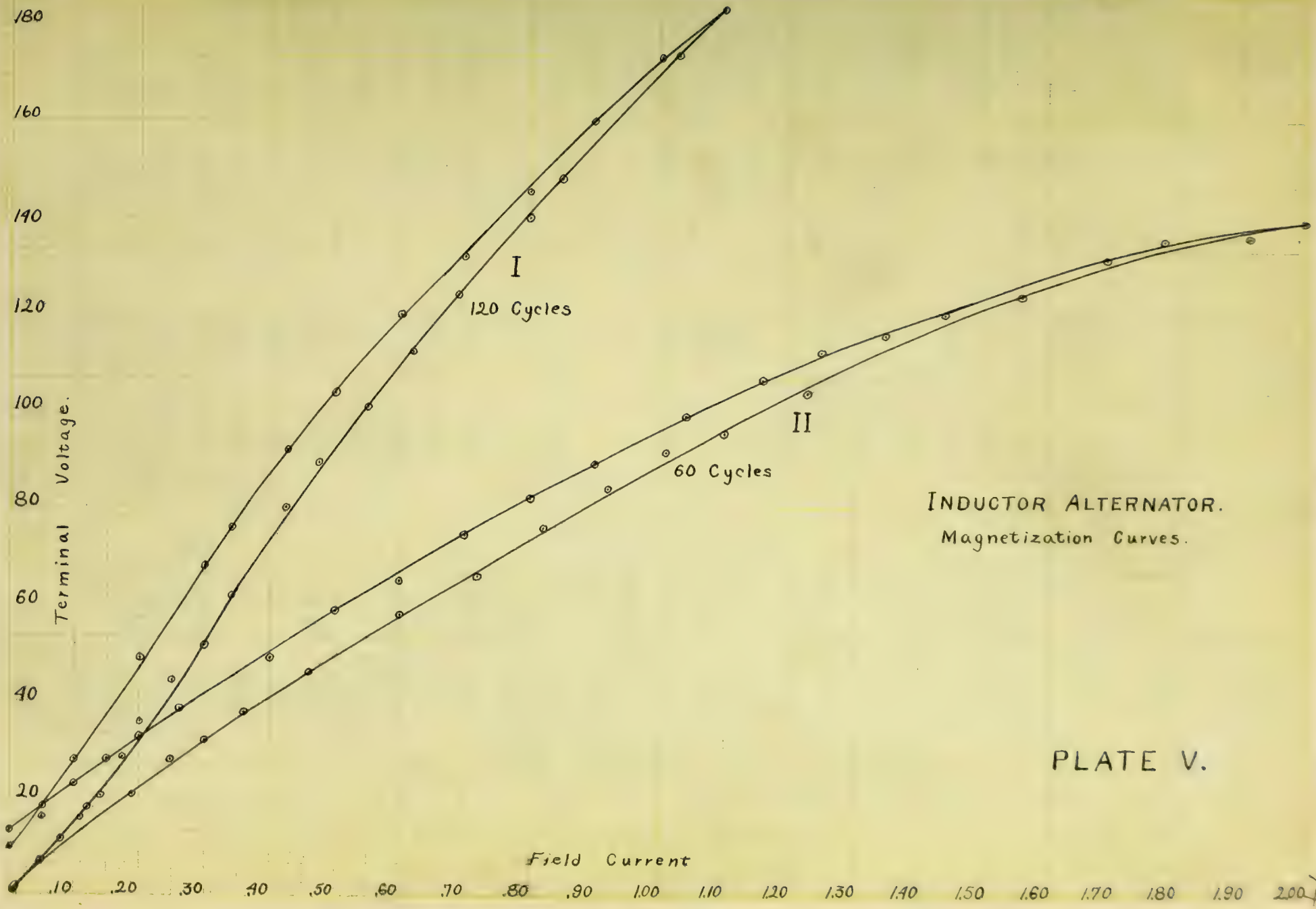
The curve also have many of the characteristics of the castiron magnetization curve which material predominates in the magnetic circuit of the machine.

The magnetization curve for a sample of the castiron used in the machine is shown in Plate VI.

Regulation Test.

The object of this test was to find the pressure produced at the terminals of the machine under various conditions of loading, i.e. non-inductive with unity power factor, capacity with .80 power factor, and inductive load with .80 power factor.

The speed was adjusted to 60 cycles and was maintained constant throughout the test. Full load current was first obtained under each condition of loading at normal pressure.



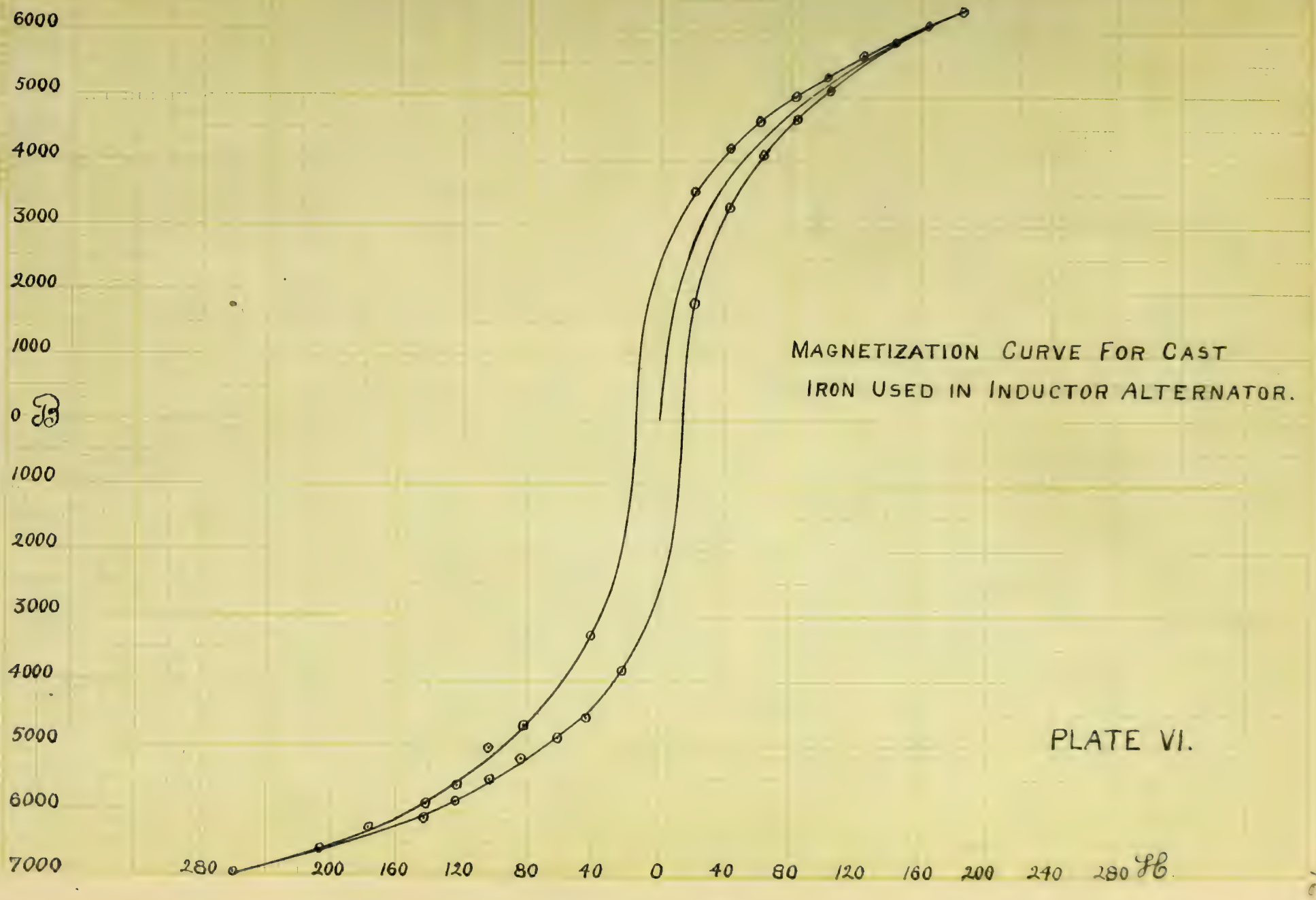
INDUCTOR ALTERNATOR.

Magnetization Curves.

PLATE V.

DATA FOR MAGNETIZATION CURVES.

120 CYCLES.			60 CYCLES.					
E	I_f	Speed	E	I_f	Speed	E	I_f	Speed
0	0	1440	104.0	.500	1440	104.5	1.230	720
11.0	.080	..	91.0	.425	..	113.0	1.350	..
18.0	.120	..	75.5	.345	..	124.0	1.560	..
20.5	.140	..	68.5	.300	..	131.0	1.780	..
28.5	.175	..	59.5	.250	..	136.0	1.910	..
30.5	.185	..	49.7	.200	..	143.0	2.100	..
34.5	.200	..	41.0	.150	..	139.0	2.000	..
38.5	.225	..	29.0	.100	..	131.0	1.690	..
44.5	.250	..	16.0	.050	..	120.0	1.440	..
52.0	.300	..	10.0	.000	..	116.0	1.340	..
62.0	.340	..				111.0	1.250	..
80.0	.425	..	0	0	720	106.5	1.160	..
89.5	.475	..	7.0	.050	..	98.5	1.040	..
101.0	.550	..	15.0	.110	..	90.0	.900	..
113.0	.620	..	21.0	.190	..	82.0	.800	..
125.0	.690	..	27.0	.250	..	74.0	.700	..
140.0	.800	..	31.0	.300	..	65.0	.600	..
148.0	.850	..	38.0	.360	..	59.0	.500	..
174.0	1.030	..	46.5	.460	..	50.0	.400	..
183.0	1.100	..	58.0	.600	..	39.5	.260	..
174.0	1.000	..	66.0	.720	..	34.0	.200	..
160.0	.900	..	76.0	.820	..	28.0	.150	..
146.0	.800	..	84.0	.920	..	23.0	.100	..
132.5	.700	..	91.0	1.010	..	18.0	.050	..
120.0	.600	..	97.0	1.100	..	14.0	.000	..



MAGNETIZATION CURVE FOR CAST IRON USED IN INDUCTOR ALTERNATOR.

PLATE VI.

Using the required field current to obtain this condition, a series of readings was taken of armature current and pressure while the armature current was varied from above full load, to zero, The power factor in the last two cases being maintained constant at .80 by adjusting the capacity or inductance in parallel with resistance until the proper result was obtained.

The curves from these data are shown in Plate VII. Curve I is the noninductive characteristic. The rise in voltage between full load and no load is 22 volts $\frac{22}{110} \times 100 = 20\%$ regulation between full load and no load. This is considered good for this type of machine.

Inductive load, however, gives a steper characteristic The regulation being $\frac{40}{110} \times 100 = 36\%$

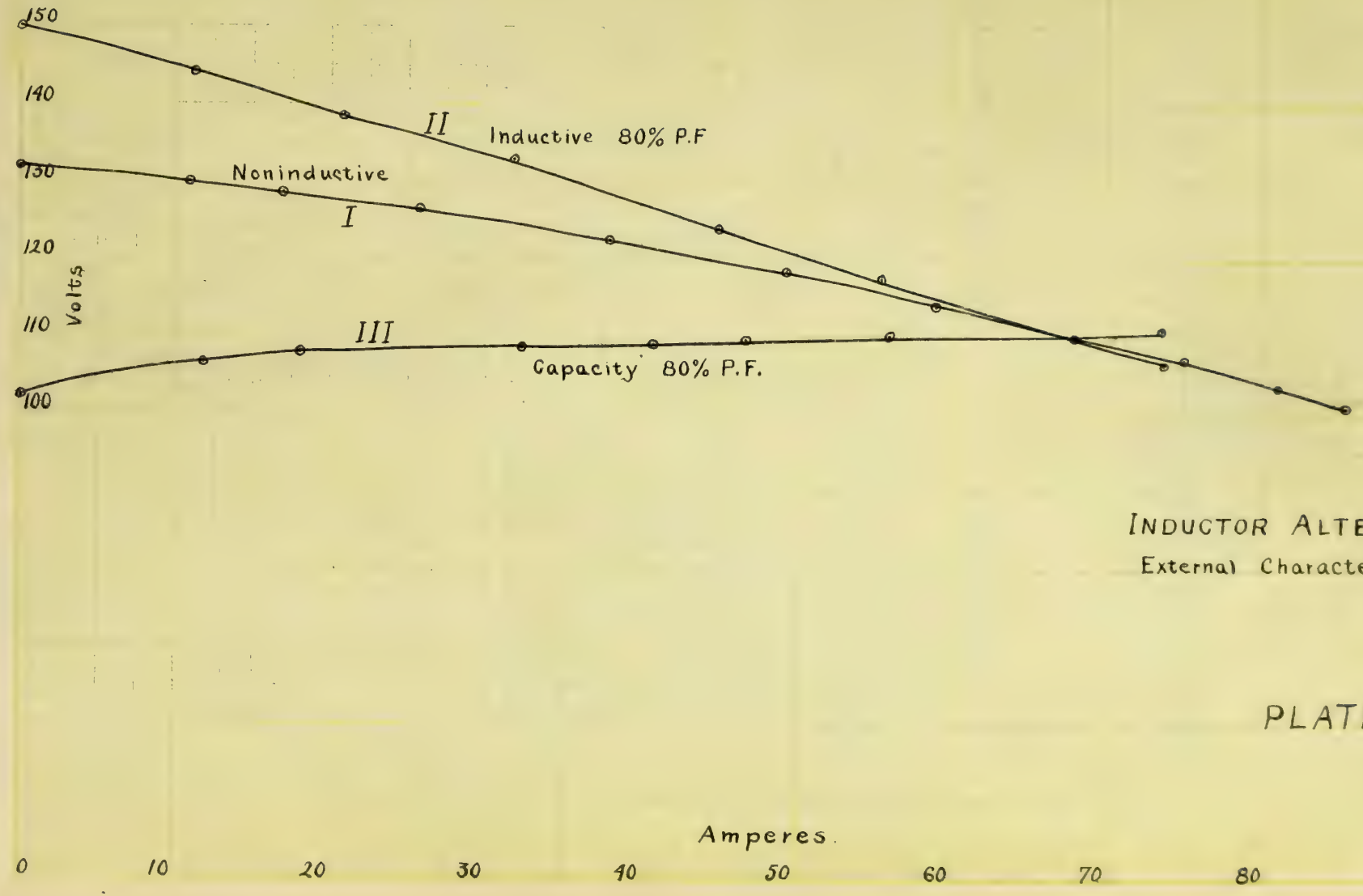
Capacity load gives a regulation which is negative $\frac{-8}{110} \times 100 = -7.3\%$, the characteristic being nearly horizontal

for most of its length. This shows that the inductor alternator regulates well on a capacity load

Synchronous impedance.

For this test the machine was first short circuited through an ammeter and the field current was raised to such a value as to produce full load current in the armature. A series of readings was taken of field and armature currents while the field current was reduced to zero. Using the same values of field current, another series of readings of pressure on open circuit was taken. This is the normal pressure developed in the armature.

Since E is the total pressure developed and I the total current produced by it when there is no external resistance or reactance in the circuit, then Z, the impedance of the armature is $\frac{E}{I}$. This impedance is composed of two vectors, one composed of armature resistance R



INDUCTOR ALTERNATOR.

External Characteristics.

PLATE VII.

DATA FOR EXTERNAL CHARACTERISTICS.

Non Inductive		Capacity			Inductive		
E	I	E	I	W	E	I	W
110.0	68.0	110.0	68.0	6.00	110.0	68.0	6.00
101.0	85.5	102.0	00.0	0.00	150.0	00.0	0.00
103.5	81.0	111.0	76.0	6.70	106.5	73.6	6.25
107.0	75.0	110.0	56.0	4.90	117.5	55.2	5.20
110.5	67.0	109.5	46.8	4.10	124.0	45.0	4.50
114.0	59.0	109.0	40.7	3.55	133.0	31.7	3.38
118.5	49.5	108.5	32.4	2.81	138.5	20.7	2.30
122.5	38.0	106.5	11.8	1.00	144.0	11.5	1.33
126.5	25.8	108.0	18.0	1.55	150.0	00.0	0.00
128.5	17.0	102.0	00.0	0.00			
130.0	11.0						
132.0	00.0						

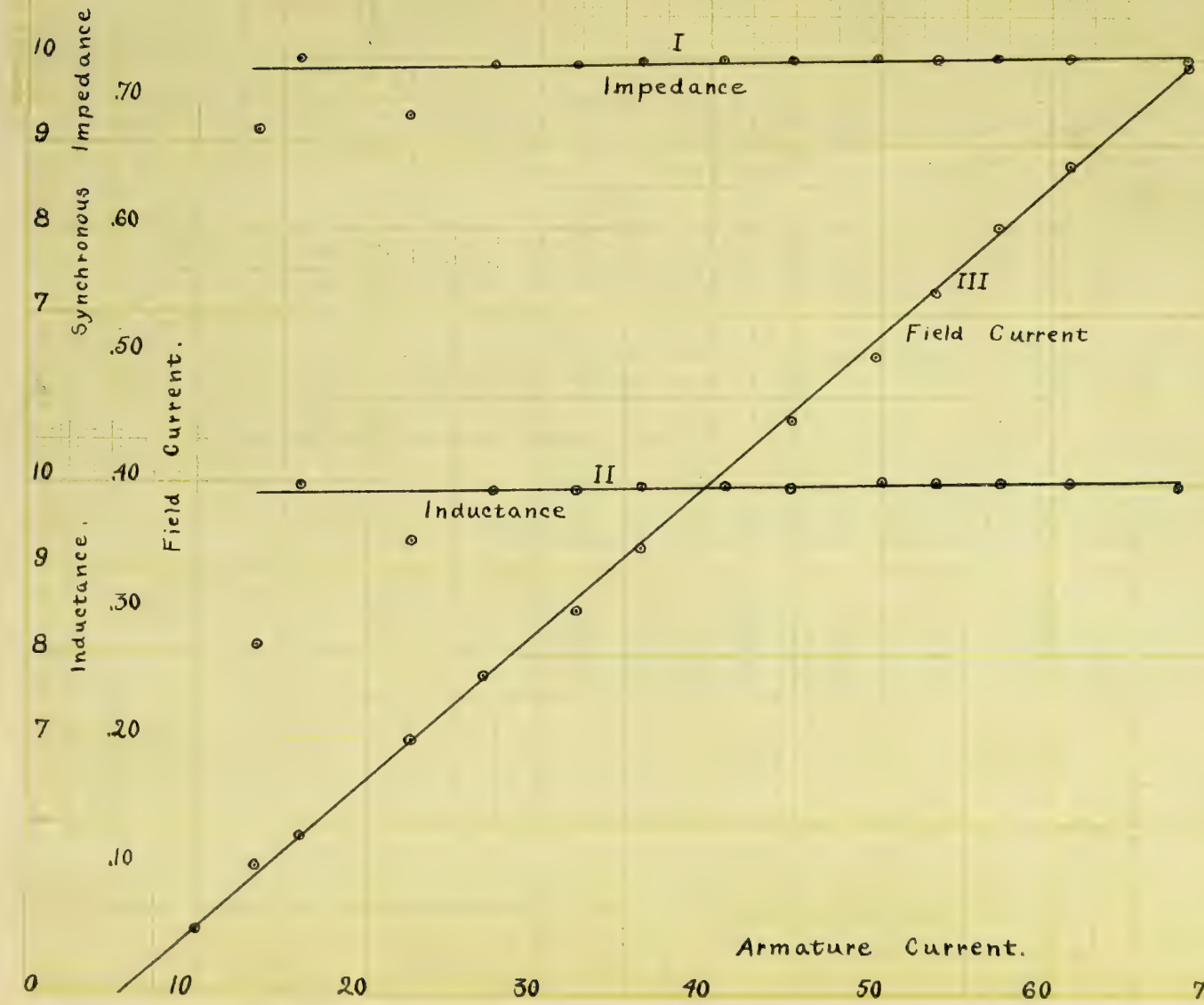
which was obtained by the drop of potential method. The synchronous reactance was then obtained by the formula $X = \sqrt{Z^2 - R^2}$.

Curves were plotted as shown in Plate III armature current being used as abscissae and synchronous impedance synchronous reactance and field current as ordinates. The synchronous reactance is large compared to the armature resistance; hence in the formula $X = \sqrt{Z^2 - R^2}$, X very nearly equals Z.

Temperature Test.

With the machine running on full load, it was desired to investigate the rise of temperature in the various parts of the machine.

For this test thirteen thermometers were used, distributed as follows, four on the armature yoke, two on the armature coils, two on the field coil, one on each bearing and three hung near the machine to record the room temperature.



INDUCTOR ALTERNATOR.

Synchronous Impedance,
Inductance, and Field Current Curves.

PLATE VIII.

DATA FOR SYNCHRONOUS IMPEDANCE

I_f	I_A	E	Z	L
.73	68.0	68.0	1.000	.998
.65	61.0	61.5	1.010	1.008
.60	57.0	58.0	1.015	1.013
.55	53.3	54.8	1.030	1.027
.50	49.3	50.0	1.010	1.008
.45	44.8	45.0	1.000	.998
.40	41.0	41.0	1.000	.998
.35	36.0	36.0	1.000	.998
.30	32.2	32.0	.995	.993
.25	27.2	27.0	.994	.990
.20	22.5	21.0	.935	.931
.13	16.0	16.0	1.000	.998
.10	13.5	11.0	.815	.812

The machine was started at full load of 68 amperes and 110 volts, and was maintained at this value throughout the test, which lasted 13 hours. The thermometers were read at the start and at five, fifteen, and twenty-five minutes thereafter and then every fifteen minutes until the test had been in progress six and one-half hours. For the rest of the run, the thermometers were read every half hour. The several thermometer readings for each part of the machine were averaged and the average was taken as the temperature of that part. These readings were then corrected for a room temperature of 25° C. by adding or subtracting ½% for each degree of room temperature above or below 25° C., respectively.

Using these corrected values of temperature as ordinates, curves were plotted using time as abscissas. These curves are shown on Plate IX. Curve I shows the rise of temperature

in the field coil, II in the armature winding, III in the armature iron, and IV in the bearings.

The temperature rise in the field coil was not so rapid at first; it cover the armature coil curve, which rose more rapidly at first, at the end of six hours, and at the end of the test was about four degrees warmer than the amature coils. The ultimate temperature of the field coil was 82°C. or 57°C. above a room temperature of 25°C. The cause of this high temperature in the field coil is due largely to faulty design. The only surface of the spool which receives the fanning action of the rotor is the end, and since the spool is six inches thick from end to end, the proportion of cooling surface is very small. On the convex surface of the spool where it is open to the air through the ventilating ducts, the draft is poor because the only inducement for a flow of air is created by the heat of the coil itself. The design might have

bars improved by making the coil in two parts with a ventilating duct between the parts or by making the coil thinner and larger in diameter.

The rise of temperature in the armature ring was quite large due to the large hysteresis and eddy current losses. Excessive rise in temperature however was prevented by the large cooling area.

The bearings of the machine ran very smoothly and heated less than any other part of the machine, the maximum rise being only about 20°C. above room temperature.

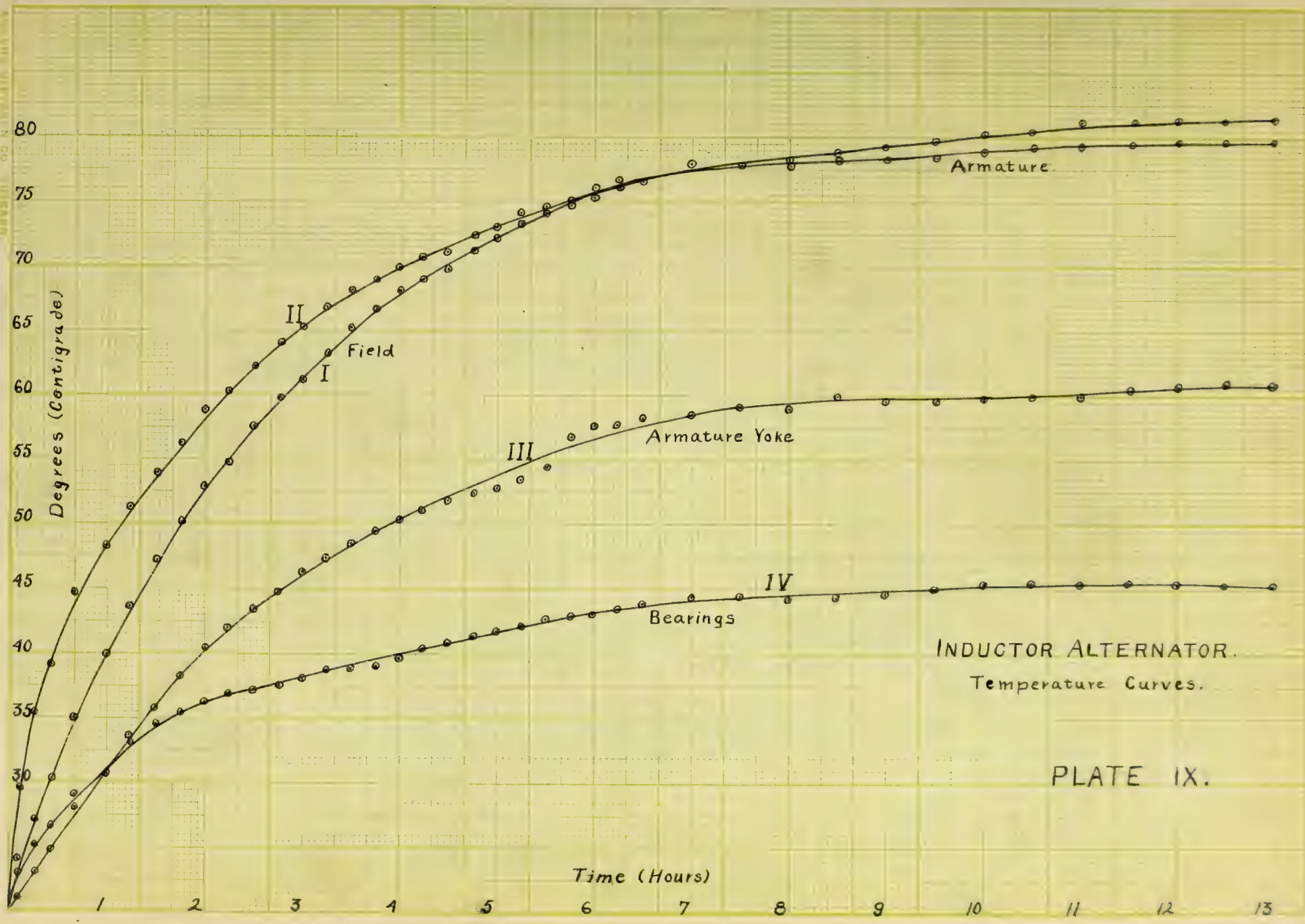
The resistances of the armature and field were taken both before and after the test. The temperature rise as calculated by the change in resistance caused by heating, is as follows.

$$\theta = (238.1 + 20°)\left(\frac{603}{473} - 1\right) = 71.3°C. = \text{Field}$$

Temperature rise above 25°C. room temperature.

$$\theta\,(238.1 + 20.5°)\left(\frac{.074}{.0014} - 1\right) = 52.5°C. = \text{Armature}$$

rise above 25°C. room temperature.



INDUCTOR ALTERNATOR.

Temperature Curves.

PLATE IX.

DATA FOR TEMPERATURE CURVES

Time	Room	Bearings	Yoke	Field	Armature	If
0.00	21.3°	20.6°	20.1°	20.8°	20.5°	1.75
0.05	22.0	23.0	21.0	24.1	29.6	1.76
0.15	21.8	25.1	23.0	27.1	35.5	1.78
0.25	21.7	26.6	24.8	30.2	39.2	1.80
0.40	22.0	29.1	28.0	35.0	44.8	1.82
1.00	22.5	31.6	31.2	40.0	48.3	1.83
1.15	22.6	33.2	33.7	43.6	51.3	1.84
1.30	22.2	34.6	35.7	47.2	54.0	1.85
1.45	23.0	35.5	38.2	50.1	56.3	1.85
2.00	239	36.9	40.5	53.0	59.0	1.86
2.15	23.8	37.0	42.0	54.8	60.4	1.86
2.30	23.7	37.2	43.5	57.6	62.4	1.86
2.45	23.5	37.6	44.9	59.9	64.2	1.86
3.00	23.9	38.1	46.4	61.2	65.4	1.87
3.15	23.7	38.9	47.5	63.4	67.0	1.88
3.30	24.2	39.0	48.5	65.2	68.2	1.89
3.45	24.4	39.3	49.5	66.9	69.1	1.89
4.00	24.9	39.9	50.4	68.2	70.0	1.89
4.15	25.6	40.5	51.0	69.0	70.8	1.92
4.30	25.8	41.0	51.7	69.9	71.7	1.92
4.45	25.8	41.5	52.3	71.2	72.5	1.92
5.00	26.3	41.7	52.9	72.1	73.2	1.92

5.15	26.6	42.3	53.5	73.4	74.2	
5.30	26.9	42.8	54.5	74.2	74.9	
5.45	26.8	43.0	56.7	74.8	75.2	
6.00	27.3	43.3	57.7	75.3	76.2	
6.15	27.1	43.5	57.8	76.7	76.1	
6.30	26.7	44.0	58.4	76.6	76.6	
7.00	26.7	44.5	58.6	78.0	77.8	Became Constant.
7.30	26.2	44.5	59.2	77.9	77.9	
8.00	25.5	44.3	59.0	78.3	77.7	
8.30	24.3	44.5	60.0	78.8	78.3	
9.00	26.0	44.8	59.6	79.4	78.4	
9.30	25.9	45.1	59.9	80.2	79.4	
10.00	25.5	45.5	59.7	80.3	79.4	
10.30	25.3	45.6	60.0	80.5	79.6	
11.00	25.0	45.5	60.0	81.1	79.8	
11.30	24.7	45.6	60.5	81.3	79.9	
12.00	24.7	45.5	60.9	81.4	79.9	
12.30	24.6	45.3	61.0	81.3	79.8	
13.00	24.7	45.4	60.9	81.3	79.9	

Resistance of field at beginning 47.3 ohms
at end of test 60.3 ohms.

Resistance of armature at beginning .0614
ohms at end of test .0740 ohms.

Highest armature reading	82.05°
Highest field reading	81.5°
Leading pole tip	61.0°
Trailing pole tip	62.9°

Separation of Hysteresis and Eddy current Losses.

Since the iron losses of the machine are so heavy it was desired to find out how the losses compared with each other.

The machine was run with a constant field, then the hysteresis varies directly with the number of cycles per second and the eddy current loss with their square. The resistance of the armature of the motor by which the machine was driven was measured and the I^2R curve plotted, Plate XI. The motor was then run without belt through a wide ~~range~~ of speed, and the power intake measured. The curve showing power required for each speed is shown on Plate X. The motor was then belted to the alternator. The speed of the alternator was varied from a maximum to a minimum, readings being taken of power

ment and speed. From the input was subtracted the I^2R of the motor taken from the curve, Plate XI. This power was charged up against the iron machine as friction, windage, and belt losses. A curve showing losses at different speeds is shown on Plate X. A constant field was then put on the alternator, and the machine run through the same range of speed as before, readings being taken of speed, voltage, and power input. From this input was subtracted the motor I^2R and the watts consumed by friction, windage, and belt losses taken from the curves on Plates X and XI. This gave the power consumed by the iron losses.

The watts divided by the frequency gives the joules per cycle. The area of the hysteresis loop remains constant, but the eddy currents vary as the speed. A curve was plotted, Plate XII, between joules per cycle and speed. The curve was continued until

it cut the Y-axis, and from the point of intersection a line was drawn parallel to the X-axis. This curve represents the hysteresis and the first drawn curve the eddy currents.

The hysteresis loss was high. This is due to the poor quality of the iron furnished, the castings being made, as said before, in the University foundry, using the pig-iron that was in stock. The eddy current loss was also high. This is partly due to the method of construction. The laminations were not insulated except with the iron oxide formed in the process of manufacture. The machining of the pole faces also helped to make a path for the eddy currents by bridging over the space between the sheets of metal with a burr formed in cutting.

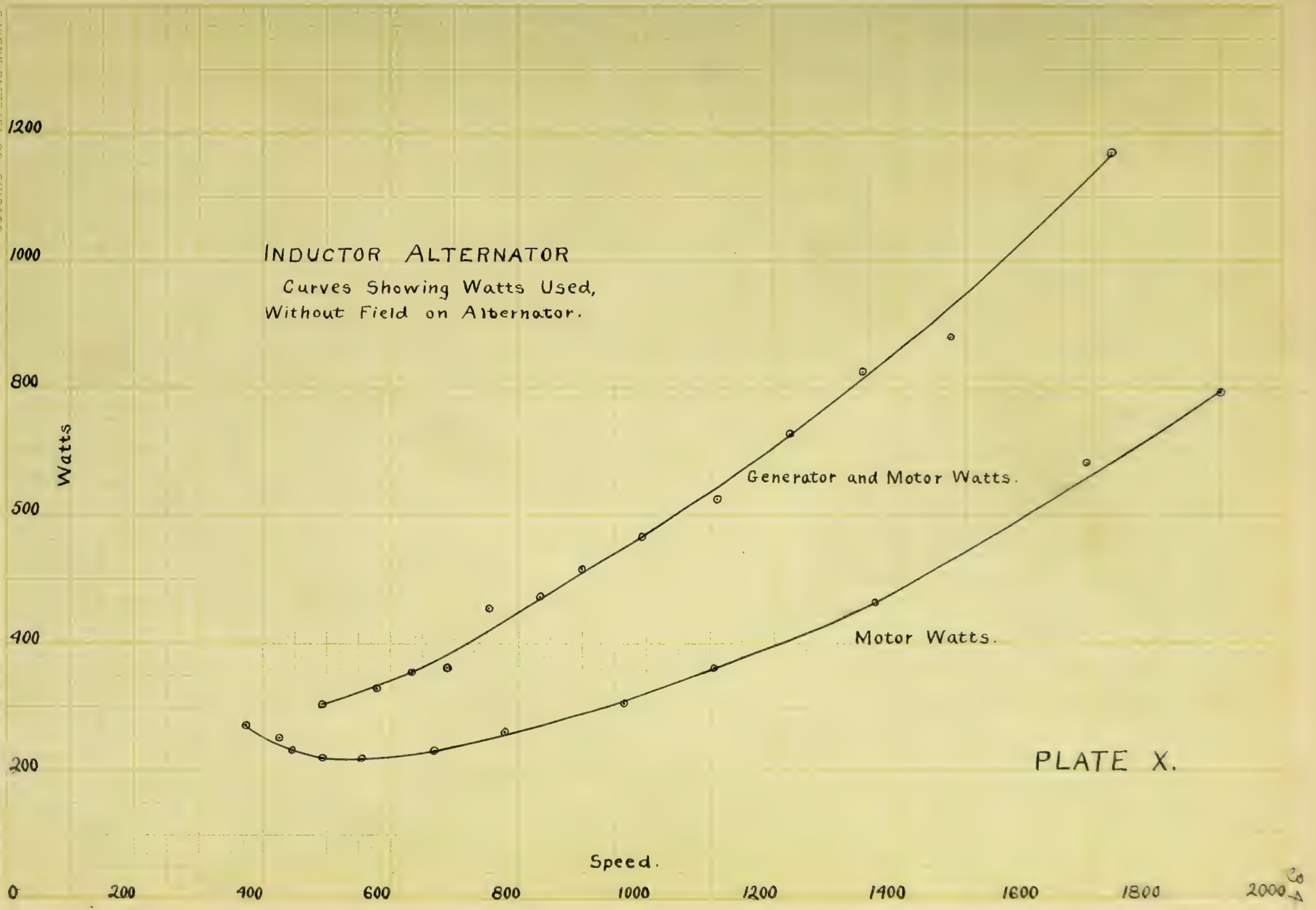
Curves were plotted between armature current, armature I^2R and field $=I$, shown on Plate XI. This gave sufficient data to figure the efficiency of the machine. The efficiency is equal

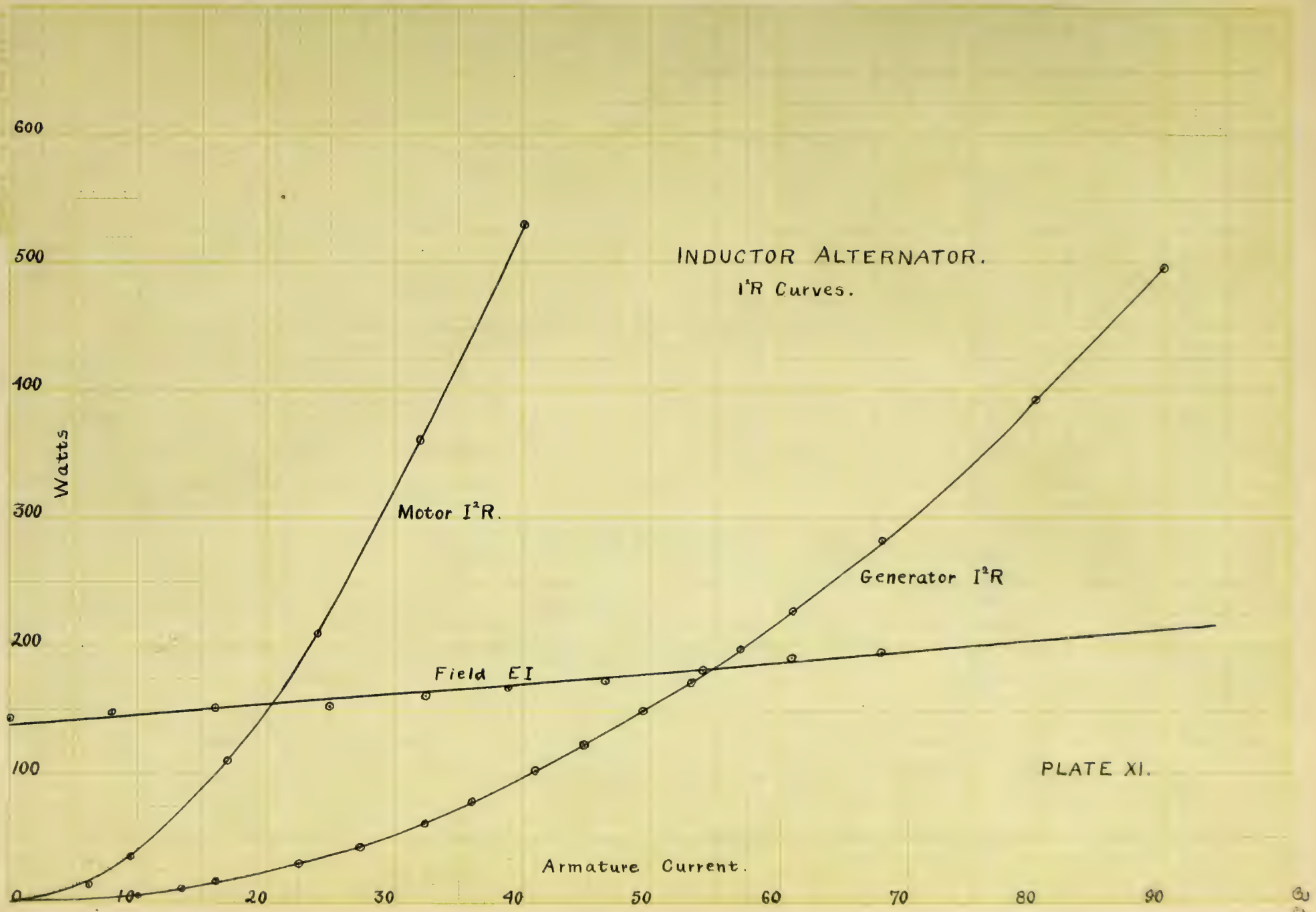
to $\frac{\text{output}}{\text{output} + \text{losses}}$

The losses are field copper losses, armature I^2R losses, iron losses, and friction and windage loss. The iron losses, and friction and windage are assumed constant for all loads. The iron losses were taken from curve of Plate XII. The joules per cycle were taken for 720 R.P.M., which gave 60 cycles; This multiplied by 60 gave the iron losses, which amount to 1608 watts. Friction and windage was taken from curve on Plate X, and from this was subtracted the power to drive the motor taken from curve on the same plate. This gave 157 watts, which included the belt losses. As there was no means of measuring these, they were assumed to be 50 watts. This gave 107 watts for friction and windage. From curves on Plate XI, the armature I^2R watts, 280, and the field I^2R, 196, watts at 68 amperes were taken, The efficiency at full load is then $\frac{7500}{7500 + 1608 + 107 + 280 + 196} = 77.5\%$

The efficiency was calculated for ¼, ½, ¾, 1, 1¼, and 1½ load, and a curve was plotted, Plate XIII. The efficiency does not reach a maximum at full load but increases up to 50% overload and beyond. This is due to the large iron losses.

EUGENE DIETZGEN CO. CHICAGO.




INDUCTOR ALTERNATOR.
I²R Curves.
Watts
600
500
400
300
200
100
0
Motor I²R.
Generator I²R
Field EI
Armature Current.
10
20
30
40
50
60
70
80
90
PLATE XI.

DATA FOR FIELD WATTS

E	I_A	E_f	I_f	W
110	68	110	1.78	196
"	61	111	1.74	193
"	54	111	1.63	181
"	47	111	1.57	174
"	39	111	1.51	168
"	33	111	1.46	162
"	25	112	1.38	155
"	16	112	1.35	152
"	8	113	1.31	148
"	0	113	1.27	144

DATA FOR MOTOR LOSSES.

Speed	Volts	Amp.	Watts	Volts	Amp.	R	I^2R
373	220	1.25	275	2.60	5.25	.495	14
425	..	1.15	253	4.10	9.00	.456	37
444	..	1.05	231	6.60	17.00	.388	112
495	..	1.00	220	8.80	24.00	.366	211
555	..	1.00	220	11.25	32.00	.352	361
670	..	1.05	231	13.70	40.00	.342	530
780	..	1.20	264				
963	..	1.40	308				
1105	..	1.65	363				
1360	..	2.10	462				
1690	..	3.10	682				
1900	..	3.60	793				

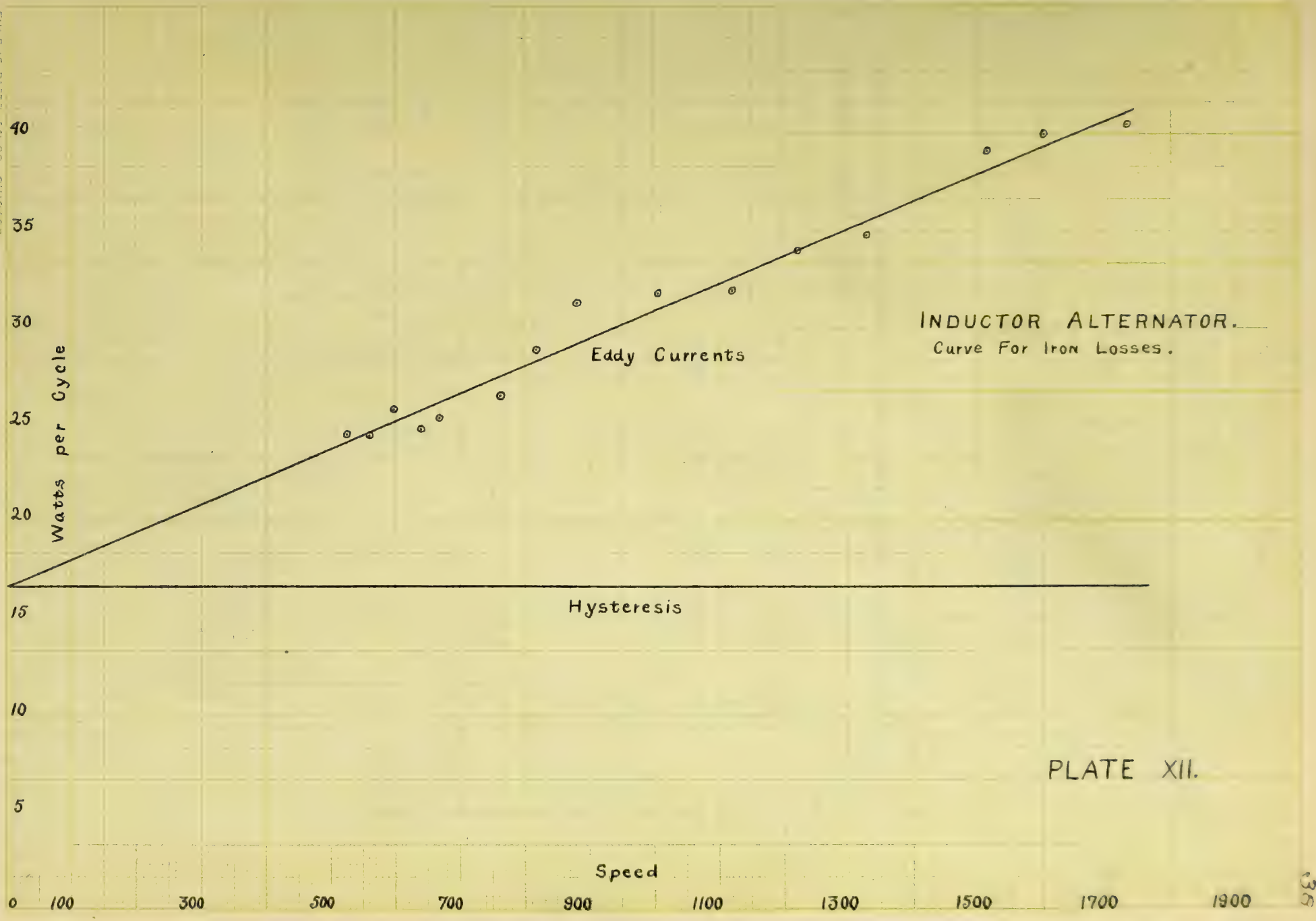


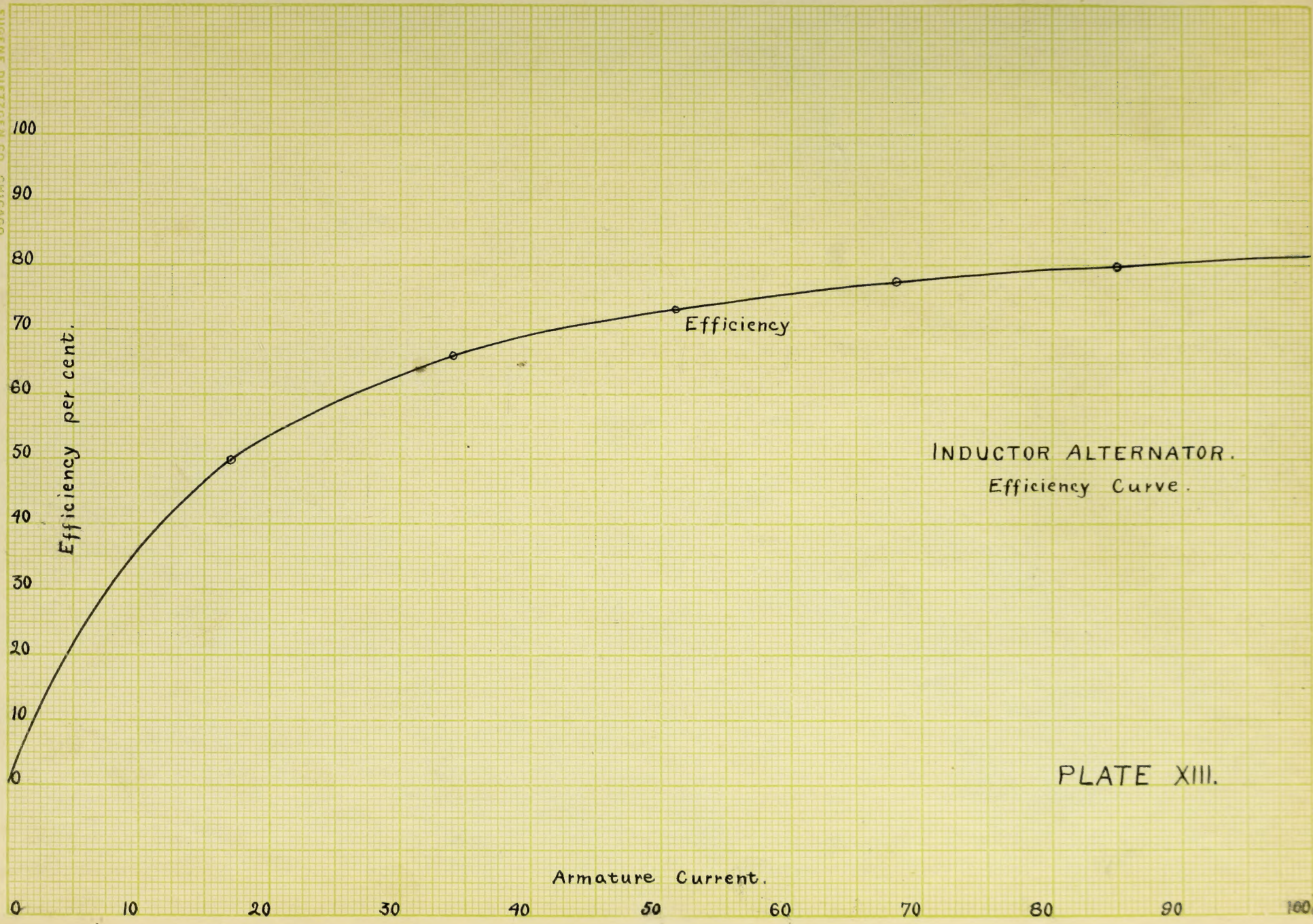
PLATE XII.

EUGENE DIETZGEN CO. CHICAGO

DATA FOR IRON LOSSES

Without Field.		Constant Field 1.5 Amperes.				Constant Voltage 110		
Speed	Watts	Speed	Volts	Watts	Joules Per Cycle	Speed	I_f	Watts
1725	1170	1730	264	5830	40.5	1762	.50	783
1475	880	1600	246	5340	40.0	1644	.54	844
1340	824	1514	231	4943	39.2	1524	.57	820
1225	726	1330	208	3835	34.8	1400	.53	810
1110	623	1220	193	3475	34.0	1228	.72	935
992	569	1120	176	2995	32.1	1110	.81	950
900	515	1002	161	2667	31.9	945	.94	1090
835	473	880	143	2290	31.3	858	1.10	1180
754	453	816	131	1965	28.9	780	1.23	1270
690	360	760	122	1671	26.4	712	1.38	1360
632	352	696	114	1467	25.3	640	1.63	1490
588	330	640	104	1322	24.8	586	1.90	1620
530	347	597	99	1285	25.8	540	2.31	1775
495	307	525	86	1070	24.5	520	2.52	1840

EUGENE DIETZGEN CO., CHICAGO.



INDUCTOR ALTERNATOR.

Efficiency Curve.

PLATE XIII.

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